Durability of concrete: prescribing composition or requiring performance?

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ABSTRACT

In order to obtain durable concrete structures, code provisions typically prescribe concrete compositions in terms of minimum cement content and maximum water cement ratio. These 'deemed-to-satisfy' rules are mainly based on long-term practical experience. However, as there is a clear trend to use alternative binders, incorporating more environment-friendly powders, the prescriptive approach in the standards can be questioned. On the one hand, classical definitions like cement content and water cement ratio can often be debated for the alternative binder systems. On the other hand, it is not clear whether the durability of concrete based on new binder systems is quantitatively having the same relation with cement content and water cement ratio. The equivalent concrete performance concept is offering a first step to a more soundly based evaluation of durability requirements for new binder types. However, this concept also has its limitations, as it is based on comparative testing still considering a deemed-to-satisfy reference concrete. A scientifically more sound solution would be obtained by requiring an absolute durability performance for the concrete to be applied in a structure. This performance could be checked in laboratory conditions (potential performance) as well as on the completed structure (as-built performance).

INTRODUCTION

After the introduction of concrete as a construction material at the end of the 19th century, during many years it was considered that concrete structures were built to last without any further maintenance or repair. In the meantime however, we have experienced that this unfortunately is not the case. Serious degradation mechanisms can severely reduce the service life of concrete structures: steel reinforcement can corrode, cement matrix can be attacked, and even aggregates can show detrimental processes. (De Schutter, 2012)

The best and most economical option to reach a target service life, is to carefully design the structure duly considering the effect of relevant aggressive actions. An important element within this approach of 'good practice' is to design a durable concrete composition. A durable concrete structure starts with a durable concrete for the considered application. Some traditional parameters are generally considered to be important for the durability of concrete: the water/cement ratio, the cement content, and the cement type. Concrete strength can give a good indication, but is certainly not a satisfying condition with regard to durability. Often neglected is the influence of the maximum particle size on the required cement content within a mix. The application of puzzolan and inert fillers, and the degree to which these fillers can be considered as cement replacing materials, is an important point of discussion in concrete practice. Casting and curing operations are also important with respect to the final durability properties of the completed structure. As a general point of attention, it should be realized that the concrete cover is crucial to some durability properties of concrete structures. (De Schutter, 2012)

CURRENT CODE PROVISIONS

A fundamental study of the durability of concrete has to start from the physical and chemical properties of the material, and needs to consider the transport properties of (potentially aggressive) liquids and gasses in the pore system. A detailed treatment of this fundamental information is out of the scope of this paper. Standards covering concrete as a material, like the European Standard EN 206, are not to be considered as scientific text books, as the fundamental background will rather be translated to practical measures which can be followed easily in practice.

As the parameters water/cement ratio and cement content have already for a long time been considered as important durability parameters, it is no surprise to see that typical code previsions related to durability of concrete are often based here on. In Europe, the standard EN 206 ‘Concrete: Specification, performance, production and conformity’ departs from the notion of exposure classes, designated with a capital letter X, followed by another letter depending on the specific degradation mechanism to be considered: C for carbonation, D for de-icing salts, S for sea water, F for frost, and A for chemically aggressive environment. To this letter combination, a number is added which in most cases is linked to specific humidity conditions. In total 18 exposure classes have been defined, as listed in Table 1. Depending on the environment, several degradation mechanisms can occur in parallel. Therefore, it is necessary to select all relevant exposure classes for the considered application. Finally, the concrete composition will have to be designed considering the most severe exposure class.

The durability requirements linked to the listed exposure classes are expressed in terms of a maximum allowable water/cement ratio and a minimum needed cement content. These limiting values are mainly based on practical experience, and are not the result of clearly documented scientific calculations. In an indicative way, also strength classes are mentioned. All requirements in terms of water/cement ratio, cement content and strength are locally defined in each European member state. The code provisions of the ‘place of use’ should be followed when producing concrete elements in Europe.

A similar approach is followed in many other international standards, like the North American Standard ACI 318:2008, the Canadian Standard CSA A23.1:2004, the Australian Standard AS 3600:2001, and the Indian Standard IS 456-2000. Some exposure classes are defined referring to the anticipated severity of the environment of the concrete element. The exposure classes are subdivided, e.g. depending on humidity conditions. According to the exposure (sub)class, limiting values are specified for water/cement ratio and compressive strength in the North American, Canadian and Australian standard, while a minimum cement content is also required in the European Standard. Additional requirements might be added in some cases, like high sulfate resisting cement (EN 206-1). A comprehensive overview is given by Kulkarni (2009).

Table 1. Exposure classes defined in European Standard EN 206

X0	**No risk of corrosion or attack**
XC	**Corrosion induced by carbonation**
XC1	Dry or permanently wet
XC2	Wet, rarely dry
XC3	Moderate humidity
XC4	Cyclic wet and dry
XD	**Corrosion induced by chlorides other than from sea water**
XD1	Moderate humidity
XD2	Wet, rarely dry
XD3	Cyclic wet and dry
XS	**Corrosion induced by chlorides from sea water**
XS1	Exposed to airborne salt but not in direct contact with sea water
XS2	Permanently submerged
XS3	Tidal, splash and spray zones
XF	**Freeze/thaw attack with or without de-icing salts**
XF1	Moderate water saturation, without de-icing agents
XF2	Moderate water saturation, with de-icing agents
XF3	High water saturation, without de-icing agents
XF4	High water saturation, with de-icing agents or sea water
XA	**Chemical attack**
XA1	Slightly aggressive chemical environment
XA2	Moderately aggressive chemical environment
XA3	Highly aggressive chemical environment

CODE PROVISIONS QUESTIONED

Concrete codes typically consider three important parameters in order to guarantee durable concrete structures: water/cement ratio, cement content, and strength. While this approach has the advantage of being practical, it is clear that each of the parameters is being criticized.

It is clear that concrete strength is not a satisfying parameter to guarantee durable behaviour (Neville 1997). A prescribed minimum cement content is also encountering criticisms in literature, as illustrated by Wasserman et al. (2008). And on top of that, while it is commonly considered as the most important practical parameter when considering durability, even the water/cement ratio should be considered cautiously. Neville (1999) states that '*We should remember the limitations on its interpretation*'. Indeed, as long as the concrete binder is made of Portland cement and water, the definition of water/cement ratio is quite clear and not questioned. In this case, there is also a clear link between water/cement ratio and strength, as e.g. illustrated in Feret's law. Nevertheless, it has to be stated that even the historic evolution of cement properties has led to an increased durability risk when only looking at concrete strength and/or cement content, as clearly shown by Neville (1997) and De Schutter (2001).

Nowadays, considering the application of various types of supplementary cementitious materials, the definition of water/cement ratio is not straightforward. The European code EN 206 considers this problem by adopting the k-value concept, as e.g. explained by Neville (1999). Although this k-value concept seems to be working for many cases, major discussions are going on about the level of the k-value and about the general validity of the k-value concept. As the k-value concept is principally based on concrete strength, the link with durability behaviour is not always straightforward. In Europe, the defined k-values differ from member state to members state, as listed in the various national application documents related to EN 206.

As an example of the European diversity within the application of the k-value concept, it can be mentioned that some countries define a k-value for the case of limestone filler, which in principle is a non-reactive filler (type I). While limestone filler is accelerating the hydration of Portland clincker due to improved nucleation possibilities, is not chemically active (except for a minor percentage which could be chemically active in the formation of carboaluminates) (Poppe & De Schutter 2005, Ye et al. 2007, Kadri et al. 2010). In this way, limestone filler improves the strength development (hence the definition of a k-value within some countries), while the improvement by limestone filler of the pore structure and the long term durability performance is not always of the same degree (De Schutter & Audenaert 2008).

Considering the criticisms on water/cement ratio, cement content and concrete strength, attempts have been made to rely on other parameters, like water absorption by immersion. This is also implemented in the EN 206, as a potential additional requirement. Nevertheless, also the water absorption by immersion can be generally questioned as a governing durability parameter (De Schutter & Audenaert 2004).

In summary, recent research results seem to seriously question and criticize the traditional parameters as a sound and generally valid basis for durability evaluation. Although these parameters might work for very traditional systems entirely based on Portland cement, it is clear that for modern binder systems, based on a combination of a multitude of reactive and even non-reactive powders, the traditional parameters are not very reliable, and only give a rough indication. The k-value concept is not very helpful in this respect, and only seems complicate the discussion, with obvious contradictions between composite binders produced in cement factory (fully considered as cement) and chemically identical binders obtained by adding powders in the concrete plant (only partly considered as cement). A more fundamental approach, based on real durability performance, is needed.

REQUIRING DURABILITY PERFORMANCE

The current mode of operation regarding durability is to specify required cement contents and water/cement ratios as mentioned before. Suppose we would follow the same approach to specify the workability of concrete. Then, the codes would e.g. be specifying a minimum water content, based on practical experience. And a superplasticizer could be taken into account by defining some equivalency factor, e.g. stating that one litre of SP is equivalent to 10 liter of water. With our current knowledge and mode of operation, this sounds ridiculous… nevertheless, it is exactly the way concrete standards are actually dealing with durability.

It is clear that in current standards, workability is handled with by requiring the real performance (e.g. a specific slump class), and by testing whether the produced concrete actually meets the specified requirement (e.g. by slump tests). A similar approach is followed for concrete strength, by specifying a strength class, an verifying by testing (compressive tests on cylinders or cubes). Although mix design parameters like water content, cement content,… are very relevant in order to reach the specified workability and strength performance, the codes are not specifying required values in order to reach the required performance. A skilled person with knowledge of concrete technology will be able to perform the mix design, supported by material’s laws and models, in view of the targeted performance. Simple tests will help verifying whether the real performance is meeting the required performance. In principle, this approach could be followed for durability as well.

Durability performance classes could be defined, e.g. for carbonation. One such class could e.g. describe a performance requirement limiting the carbonation depth after 50 years of exposure to a maximum of 20 mm. Similar durability resistance classes could be defined for chloride penetration, frost attack, sulfate attack, …Verification of the performance requirements could be done by accelerated testing in laboratory, and even by testing the real concrete on site.

Although this principle is very simple and straightforward, it is true that a serious bottleneck at this moment exactly is the availability of generally accepted and reliable accelerated durability test methods of which the obtained results can be clearly linked to performance in real conditions. Nevertheless, it is to be said that accelerated durability tests do exist, and are applied already in the framework of the equivalent concrete performance concept (ECPC) as defined in the European Standard EN 206, and detailed e.g. in the Belgian Standard NBN B15-100. Within this ECPC, the performance as measured by the accelerated durability tests is compared with the performance of generally accepted reference concretes (which are complying with the prescriptive durability tables in the EN 206). However, it is in principle not very complicated to try to define some absolute performance criteria to be met in the accelerated laboratory tests. The translation to the durability performance in real exposure conditions is then still one step further, a step which can be made in due time.

Besides accelerated durability tests in laboratory, some conventional performance tests on the real concrete in the real structure can also be very helpful. In this way, the concept of durability indicators (Baroghel-Bouny et al. 2009), can go along with the new concept of durability performance testing in laboratory, based on correlation studies and materials science. Some advanced examples of this approach can already be found in some countries, as reported elsewhere (Alexander et al. 2008). The monitoring of the real concrete by some durability indicators can be very helpful both for owner and for contractor, in view of achieving a final structure with a certified durability performance.

CONCLUSION

The current approach to deal with durability of concrete is based on a prescription of some mix design parameters, such as cement content and water/cement ratio. This approach is based on long-term practical experience with traditional concrete mixtures, and not on a fundamental scientific study. Concrete conforming to these prescriptive rules are ‘deemed to satisfy’. This prescriptive ‘deemed to satisfy’ approach does not seem very reliable for new binder types consisting of a blend of several powders. In order to come to a reliable concept for durability specifications, a performance based concept is desirable, based on durability performance classes, and a verification based on testing. In this way, the durability specification could come to the same performance level as for workability and strength. Accelerated laboratory tests could be accompanied with durability indicator tests on site. This approach can be very helpful both for owner and for contractor, in view of achieving a final structure with a certified durability performance.

REFERENCES

Alexander, M.G., Ballim, Y. & Stanish, K. (2008) ‘A framework for use of durability indexes in performance-based design and specifications for reinforced concrete structures’, Materials and Structures, 41, 921-936.

Baroghel-Bouny V., Nguyen T.Q. and Dangla P. (2009) ‘Assessment and prediction of RC structure service life by means of durability indicators and physical/chemical models’, Cement and Concrete Composites, 31, 522-534

De Schutter, G. (2001), 'Evolution of cement properties in Belgium since 1950', *Magazine of Concrete Research*, 53, 5, 291-299.

De Schutter,G. & Audenaert, K. 2004, ‘Evaluation of water absorption of concrete as a measure for resistance against carbonation and chloride migration’, *Materials and Structures*, 37, 273, 591-596.

De Schutter, G. & Audenaert, K. 2008, ‘Final report of RILEM TC 205-DSC: durability of self-compacting concrete’, *Materials and Structures*, 41, 225-233.

De Schutter G. (2012) ‘Damage to Concrete Structures’, CRC Press, Taylor & Francis Group, Boca Raton, USA, ISBN 978-0-415-60388-1, 2012, pp.189.

Kadri, E-H., Aggoun, S., De Schutter, G., & Ezziane, K. 2010, ‘Combined effect of chemical nature and fineness of mineral powders on Portland cement hydration’, *Materials and Structures*, 43, 5, 665-673.

Kulkarni V.R. (2009) ‘Exposure classes for designing durable concrete’, The Indian Concrete Journal, March, 23-43.

Neville, A.M. (1997), ‘Maintenance and durability of structures’, *Concrete International*, November, 52-56.

Neville, A.M. (1999), ‘How useful is the water-cement ratio’, *Concrete International*, September, 69-70.

Poppe, A.-M. & De Schutter, G. 2005, ‘Cement hydration in the presence of high filler contents’, *Cement & Concrete Research*, **35**,2290-2299.

Wasserman, R., Katz, A., & Bentur, A. (2008), ‘Minimum cement content requirements: a must or a myth’, *Materials and Structures*, DOI 10.1617/s11527-008-9436-0.

Ye, G., Liu, X., De Schutter, G., Poppe, A.-M., and Taerwe, L. 2007; ‘Influence of limestone powder used as filler in SCC on hydration and microstructure of cement pastes’, *Cement & Concrete Composites*, 29, 94-102.